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SULFIDE DEPOSITION AT NORANDA CREEK, BRITISH COLUMBIA



by

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A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES
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THE UNIVERSITY OF ALBERTA
FACULTY OF GRADUATE STUDIES

The undersigned certify that they have read and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled "Sulfide Mineralization at Noranda Creek, British Columbia" submitted by Kenneth John Kirkland, B.Sc.(Hons), in partial fulfilment of the requirements for the degree of Master of Science.



ABSTRACT

Several aspects of sulfide mineralization within a group of meta-sedimentary and meta-volcanic rocks in southern British Columbia were studied in an attempt to determine the origin of mineralizing solutions.

Hand specimen examination indicates the sulfides were deposited during a single period of mineralization, but small scale, cross-cutting features suggest the sulfide minerals were probably deposited over a considerable period of time during which some early formed minerals were fractured and subsequently healed or replaced by later sulfides. The paragenetic sequence of sulfide minerals, as indicated by polished section examination is, from oldest to youngest:

- pyrite
- arsenopyrite
- pyrrhotite
- chalcopyrite
- bornite
- sphalerite
- galena
- tetrahedrite

Apparent filling temperatures of six primary liquid-vapour inclusions in quartz from mineralized quartz-carbonate-muscovite veins average 265°C. Assuming the inclusions formed under lithostatic pressure of 600 to 1300 bars, corresponding to a depth of approximately 6,000 to 13,000 feet, the temperature of formation of the fluid inclusions, corrected for pressure, is in the order of 320°-390°C.

A total of fifty-eight analyses of sulfur from pyrite, pyrrhotite, sphalerite, chalcopyrite and galena collected over an area of approx-

imately 1.5 square miles gave δS^{34} values ranging from -6.22‰ to +12.13‰ with a mean value of +2.33‰. The S^{34} values approach the equilibrium sequence predicted by theoretical calculations, suggesting near-equilibrium conditions were attained during sulfide deposition. Over a horizontal distance of nearly 6,000 feet pyrite, chalcopyrite, and, to lesser extent, galena showed decreasing S^{34}/S^{32} ratios with increasing distance from a nearby granodiorite batholith. Possible explanations for this change in sulfur isotopic composition are given.

A plot of sulfur isotopic fractionation versus temperature of sulfide deposition for possible co-existing sulfide pairs reveals a general pattern of higher "isotope temperatures" nearest the batholith, lower "isotope temperatures" more distant from the intrusive. This general pattern is not without contradiction, but does suggest the thermal gradient present during emplacement of the granodiorite may be more accurately measured with further work.

Two samples of biotite from the granodiorite batholith and two samples of muscovite from sulfide-bearing quartz-carbonate-muscovite veins were dated by K-Ar methods. The biotite samples gave dates of 98 m.y. and 103 m.y., while the muscovite samples gave ages of 110 m.y. and 140 m.y. There is no evidence to indicate the muscovite-bearing veins are older than the intrusive, and it is suggested radiogenic argon from sericitic quartzite host rock may have been incorporated in muscovite which formed in the quartz veins at the time of intrusion of the granodiorite batholith. This contamination of radiogenic argon would give K-Ar ages older than the true age of the muscovite.

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Chapter I

INTRODUCTION

During the summer of 1969, while employed by Noranda Exploration Company Ltd. of Vancouver, British Columbia, the writer spent two and one-half months mapping the geology of a group of mineral claims covering several copper showings near Noranda Creek* in eastern south-central British Columbia (see Figure 1). Most of the area studied in this thesis lies within this group of mineral claims.

Sample collection was carried out by the writer during August, 1969, with additional samples obtained in November, 1969, and October, 1970.

A. Location

The area studied by the writer is located in mountainous country of the Shuswap Highland in eastern south-central British Columbia at 51°30' north latitude, 119°50' west longitude. The thesis area is located on the upper slopes and ridges of a highland plateau region which is located just south of the North Thompson River valley.

* Note: In this thesis the name Noranda Creek has been applied by the writer to a small, unnamed creek (a tributary of Harper Creek) which flows southwesterly through the central region of the thesis area.

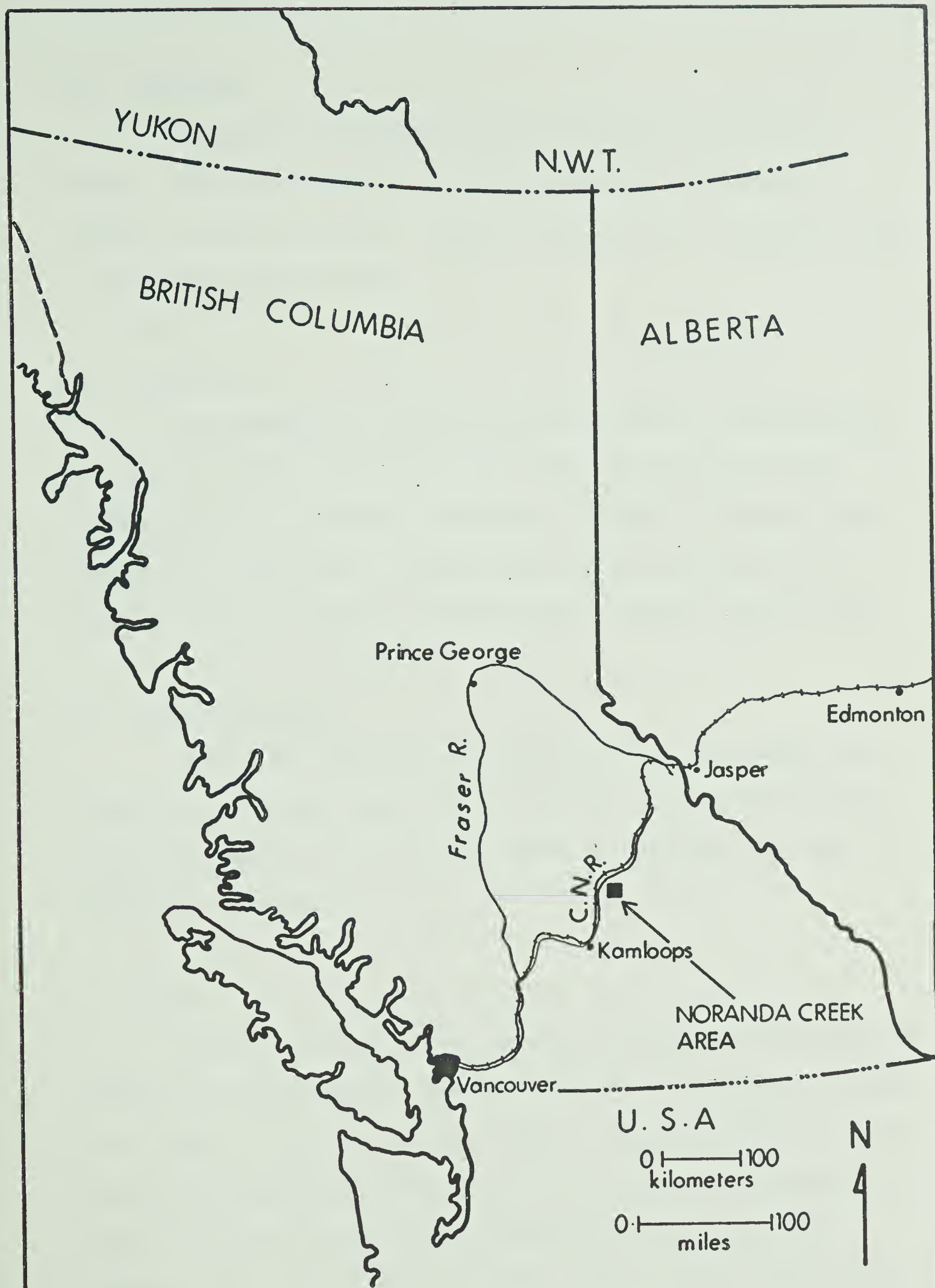


Figure 1 Location Map, Noranda Creek Area, B.C.

B. Topography

Topography is moderate to steep throughout much of the region, with most of the thesis area at elevations of 4,500 to 5,800 feet above sea level. Drainage in this area is southwest into south-flowing Harper Creek.

C. Vegetation

The southwestern and west-central regions of the thesis area are part of an old forest fire scar, within which second growth spruce and fir have become established. Fireweed is plentiful over much of the burned area. Outside of the fire scar dense forest of Engelmann Spruce, Alpine Fir and underbrush prevails over the area.

D. Outcrop Abundance

Outcrop is moderately abundant along some creek banks, but sparse to very sparse (less than 5%) over the remainder of the area. Overburden depths of 3-12 feet are common but overburden may be much thicker in some areas.

E. Access

Access to the area is via the two-lane, paved Jasper-Kamloops Highway or Canadian National Railway main line. Both means of access are located in the North Thompson Valley. From the village of Birch Island, approximately 90 miles by road north north-east of Kamloops, access is by gravel road eastward along the valley of the North Thompson River a distance of 6.4 miles, then by gravel and mud road south a distance of 9.6 miles to the site of the exploration camp

which is in the vicinity of the main mineralized area. Elevations increase from approximately 1,400 feet above sea level in the North Thompson Valley to approximately 5,300 feet above sea level at the camp.

F. Previous Work

This mineralized area was initially staked by Noranda Exploration Company Ltd. in May, 1966, after a regional geochemical silt sampling programme revealed samples with high copper concentrations from this area. Since 1966 a cut-line grid has been established on the property and soil sampling, geologic mapping, ground geophysics (including induced polarization, magnetometer, and electro-magnetic surveys), trenching (approximately 12,000 feet), and diamond drilling (approximately 25,000 feet) have been carried out.

To the best of the writer's knowledge no work prior to that completed by Noranda has been recorded for this area although several claim posts and small prospect pits, believed to date back to the 1930's, are present on the ground covered by the Noranda claims.

No mineral production has been reported from the vicinity of the thesis area although several copper and lead-zinc-silver showings have been discovered. Molybdenum, gold, and uranium-fluorite occurrences are also known in the region.

Chapter II

REGIONAL GEOLOGY

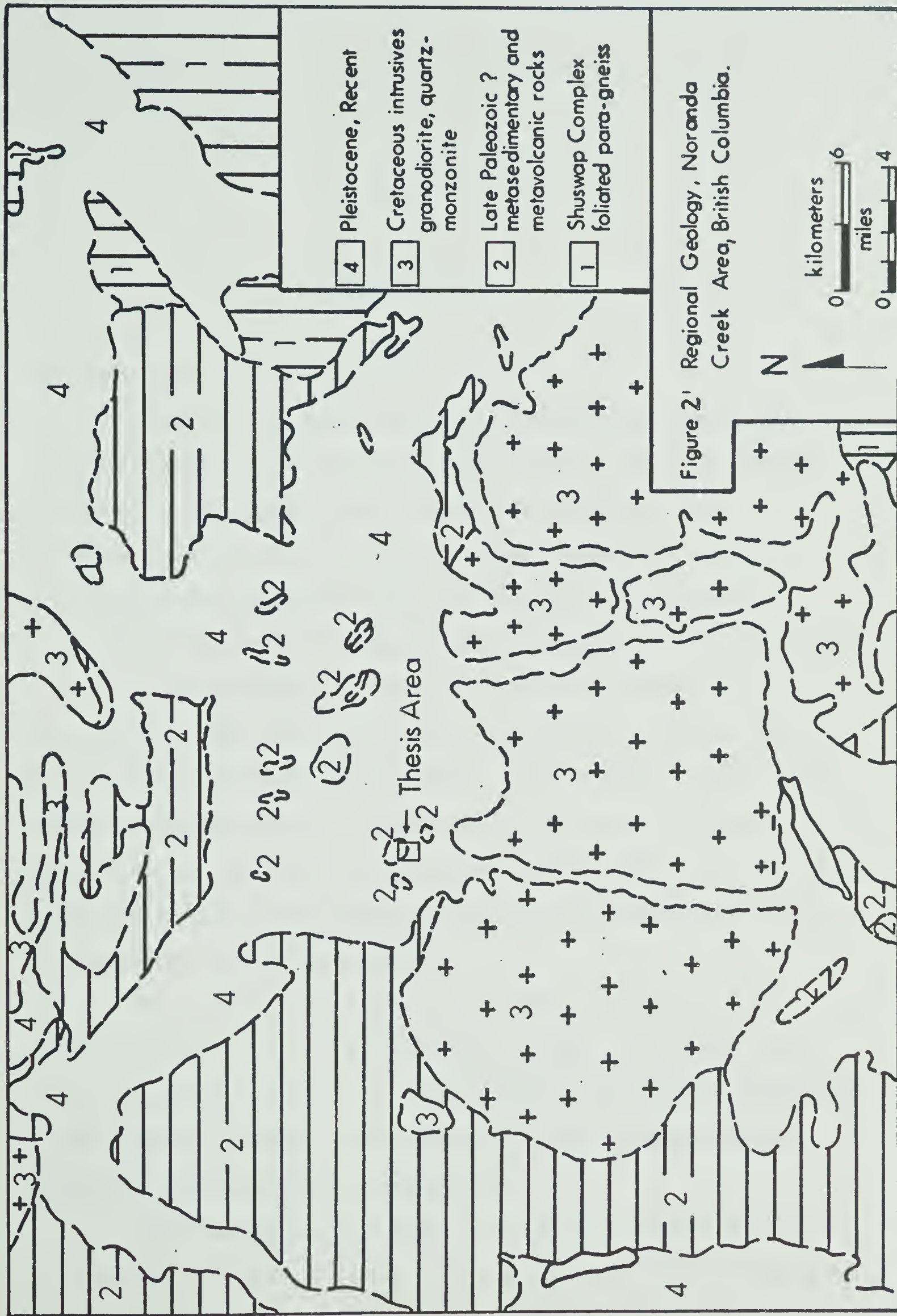
The thesis area is located on the west side of the Shuswap Complex, a high grade metamorphic terrane defined by the sillimanite isograd, and lies within a moderately metamorphosed transition zone between the high grade, regionally metamorphosed rocks of the Shuswap Complex and very weakly metamorphosed rocks to the west of the area studied. This transition zone consists mainly of Paleozoic (?) and/or Early Mesozoic eugeosynclinal sedimentary and volcanic rocks. Dr. R.B. Campbell* of the Geological Survey of Canada believes the area is one of structural complexity and has suggested the rocks exposed may range in age from Pre-Cambrian to Mesozoic. The lack of fossils or marker horizons, coupled with scarcity of outcrop makes structure and age of the rock units very difficult to decipher in the vicinity of the thesis area.

Several mid-Cretaceous batholiths of quartz monzonitic-granodioritic composition are intrusive into the Paleozoic and Mesozoic meta-sedimentary and meta-volcanic rocks exposed along the western flank of the Shuswap Metamorphic Complex. The intermediate composition and mid-Cretaceous age of these batholiths are similar to the composition and age of the Coast Intrusions which suggests a possible genetic relationship may exist between these intrusives and those of the Coast

*personal communication

Range. The intrusives in the vicinity of the thesis area occur along a semi-continuous NW-SE trending belt approximately 60 miles in length and 8-15 miles in width which is structurally terminated to the south-east by metamorphic rocks of the Shuswap Complex.

The thesis area is comprised mainly of meta-sedimentary and meta-volcanic rocks which are exposed approximately one mile from the northern margin of an elongate quartz monzonite-granodiorite batholith approximately 8 miles wide and 25 miles long (see Figure 2).



Chapter III

DETAILED GEOLOGY

A. Rock Types

Lithologies exposed in the area are mainly meta-sedimentary and meta-volcanic in nature and include: sericitic quartzite, several varieties of phyllite and schist (including sericite phyllite, chlorite phyllite, graphitic phyllite, chlorite-plagioclase schist, biotite-chlorite-plagioclase schist and numerous intermediates), re-crystallized graphitic limestone and a fragmental extrusive rhyolite (?).

Although outcrop is scarce and lithologic relations are not well known, a broad lithologic pattern can be shown. The more basic rock units; chlorite-plagioclase schist, chlorite schist, and chlorite phyllite are dominant in the western and northern parts of the area, while sericitic quartzite, sericitic phyllite and schist, re-crystallized graphitic limestone and graphitic schist are the dominant lithologies in the eastern and southern regions.

Fine grained diabase dykes were noted in two diamond drill cores in the vicinity of the main copper showings. These dykes vary from approximately 6' to 12' in width and have an attitude corresponding to the regional cleavage. The dykes appear fresh and unaltered by processes of metamorphism or mineralization.

Approximately one mile south of the Noranda property outcrops of the Baldy Batholith, a medium to coarse grained, slightly porphyritic,

biotite-hornblende granodiorite, are exposed along creek valleys. Due to lack of outcrop the exact location of the intrusive contact is unknown, but the presence of an outcrop of a sheared and chloritized intermediate intrusive in the bottom of Noranda Creek at an elevation of approximately 4,800' suggests the main intrusive mass or an apophysis of the Baldy Granodiorite occurs less than 1,000 feet below the area of mineralization. The occurrence of a highly silicified, gneissic-textured intrusive of quartz dioritic composition in diamond drill core less than 400 feet from the intrusive outcrop in Noranda Creek is additional evidence indicating the presence of an intrusive at relatively shallow depths below surface in this area.

K-Ar ages obtained by the Geological Survey of Canada on biotite from the Baldy Batholith and its extensions have given dates of 80 ± 6 m.y.¹⁸, 96 ± 5 m.y.¹⁸ and 105 ± 9 m.y.¹⁹ The quartz diorite Boss Mountain Stock which is located some 45 miles to the northwest of this area and appears to be a part of the northwest-southeast trending belt of intrusives which includes the Baldy Granodiorite has been dated at 105 m.y. (White, 1966, page 352). Highly mineralized molybdenite-bearing breccia pipes within the stock give the same ages as the quartz diorite, as determined by K-Ar analyses of hydrothermal biotite within the breccia pipes.

B. Metamorphism

Mineral assemblages in the metamorphic rocks of this area indicate these lithologies have been subjected to the quartz-albite-chlorite-muscovite subfacies of the greenschist facies of metamorphism.

Thin sections of feldspar-bearing lithologies reveal the feldspars usually weakly to moderately altered to calcite, epidote, and a very fine grained mica. Sericite predominates in altered potassium feldspars and paragonite in members of the plagioclase series. Feldspar crystals in all rock types other than diabase dykes and the Baldy Granodiorite seldom reveal any twinning, and no zoned feldspar crystals were noted in any of the thin sections. The compositions of almost all plagioclase feldspars in the metamorphic rocks were found to be albitic. The lack of twinning and zoning, and the sodic composition of the feldspars indicates regional metamorphism has re-equilibrated the feldspar grains to metamorphic conditions. This re-equilibration would involve homogenization of feldspars by ionic exchange of sodium for calcium thus removing compositional zoning and twinning.

Chlorite occurs in many of the lithologies as a result of the replacement of mafic minerals, but the replacement has proceeded so far that only rarely are vestiges of the original mafic minerals recognizable.

C. Structure

The major structural feature noted on the property is a very well developed cleavage which is exhibited by all lithologies except the diabase dykes and the granodiorite intrusive. This cleavage has a slightly variable attitude but most frequently strikes almost east-west with a dip of 20° - 45° to the north. Phyllitic and schistose rocks cleave along planes 0.5"-2" apart, whereas the sericitic quartzite usually cleaves along more widely spaced planes.

A moderate to well developed foliation due to the alignment of micaceous minerals is evident in all lithologies except diabase dykes and the granodiorite. This foliation is parallel to the cleavage.

Bedding planes, where observed, strike east-west, parallel to cleavage, but dip 5° - 10° more steeply to the north, indicating the strata are overturned.

Folding, where observed, consists mainly of small (amplitude 2'-5'), open folds which plunge 10° - 20° toward the west or west north-west. The majority of folds observed were exposed in trenches in the eastern regions of the property. Exposures in these trenches indicate the beds may be highly contorted over small areas but retain the same general attitude over a larger area.

Wheeler⁵¹ has suggested two periods of folding for all metamorphic rocks of the Shuswap area. The first period of folding produced attenuated, recumbent folds with axes trending east-west, while the second period produced open and upright folds along an axis trending northwest-southeast.

In the thesis area the first period of folding is represented by the east-west cleavage (axial plane cleavage) while the second period of folding produced the small open folds observed in some trenches. The small folds commonly plunge 10° - 20° toward the northwest (bearing 280° to 330°).

No faults were observed on the property, but numerous, narrow shear zones are reported to the east of the thesis area, and the alignment of some drainage patterns along a linear feature which strikes 030° - 210° suggests some form of structural control in this area.

A series of narrow tension fractures - strike 320° - 350° , dip usually vertical - are exposed in the area, most commonly in phyllite and schist lithologies. Locally the spacing of these fractures may be less than 1" over widths of 24"-36", but the average spacing is usually considerably greater than this. In several outcrops two distinct sizes of tension fractures were noted to occur. These two sets of fractures have the same attitude but one set is typically 1"-6" along strike, while the other set is consistently greater than 36" in length.

Kink bands up to 1" wide, and lineations on phyllite cleavage surfaces were noted at several outcrops. Both features had strikes of 120° - 300° , and the axial planes of the kink bands had dips of 55° - 80° to the southwest.

D. Sulfide Mineralogy

Sulfide minerals were observed in a variety of environments including; silicified replacement zones, quartz-muscovite-carbonate veins and veinlets, fracture coatings and fine grained disseminations. Quartz-muscovite-carbonate veins and silicified zones contained the majority of sulfide mineralization. Both veins and silicified zones frequently parallel the cleavage. All rock types contain some sulfide, with sericitic quartzite and sericite-quartz phyllite revealing the most abundant sulfide mineralization.

Sulfide species noted in the area are, in order of decreasing abundance:

py > cpy > po > gn > sph > aspy > ttd > bn > cv > cc

Pyrite mineralization is widespread but sporadic throughout the thesis area, and this sulfide occurs in all of the environments listed previously. Most commonly pyrite is associated with quartz \pm chalcopyrite, pyrrhotite in silicified replacement zones and quartz-muscovite-carbonate veins.

Chalcopyrite, like pyrite, occurs in all environments of deposition and was observed in all lithologies except diabase dykes and granodiorite. This sulfide, however, is less abundant than pyrite and although chalcopyrite is almost invariably associated with pyrite, the reverse is not always true.

Pyrrhotite occurs mainly as massive sulfide bands 4" to 16" in width replacing graphitic limestone and in places chlorite schist along cleavage planes. These replacement bands are often associated with pyrite, but small amounts of this sulfide were also noted in quartz veins, disseminated in graphite schist, and as thin coatings along margins of a few small tension fractures.

Galena and Sphalerite were observed almost exclusively within quartz veins, although small amounts of both sulfides were noted as fine grained disseminations within recrystallized graphitic limestone.

Arsenopyrite was observed in drill core from a single locality. This sulfide occurs as euhedral, fine grained crystals disseminated throughout a narrow silicified zone within phyllite.

Bornite was noted as a single small anhedral bleb within silicified phyllite. Chalcopyrite and pyrite were also present in the silicified zone, closely associated with the bornite.

Tetrahedrite was seen in a single quartz vein from the northern part of the thesis area. This mineral occurred as an anhedral mass less than 1" in size. No other sulfides were observed in contact with tetrahedrite.

On a regional scale mineral occurrences reveal a mineralogical zoning pattern around some of the Cretaceous intrusives. Gold and molybdenum occurrences are known within or marginal to the Baldy Batholith, copper occurrences are confined almost exclusively to a zone 0.5-2 miles from the granodiorite, and lead-zinc occurrences are most common 2-6 miles from the intrusive.

Hypogene zonation is also evident on a smaller scale. Within the thesis area it was noted that pyrite and chalcopyrite were the only sulfides present in the southernmost regions of the thesis area (nearest the Baldy Granodiorite) while lower temperature minerals such as sphalerite, galena and tetrahedrite were present, albeit in very small amounts, in the central and northern regions of the area.

E. Sulfide Paragenesis

On the basis of cross-cutting relationships and concentric banding textures, examination of hand specimens and polished sections from this area indicate the sequence of deposition of primary sulfides at Noranda Creek was as follows:

oldest pyrite
 arsenopyrite
 pyrrhotite
 chalcopyrite
 bornite

sphalerite

galena

youngest tetrahedrite

Stanton and Gorman (1968) reported strain on sulfide minerals frequently causes destruction of some phases and growth of other phases, producing a paragenetic sequence which may or may not correspond to the true paragenetic sequence. However, no evidence of deformation such as twin lamellae, slip planes, or bent cleavage traces were observed in polished sections of sulfides from Noranda Creek so the strain effect of Stanton and Gorman is probably not significant in the thesis area.

Magnetite has been observed in two small sulfide-bearing replacement bands, associated with pyrite \pm chalcopyrite. Textural evidence suggests the magnetite is older than chalcopyrite and may be younger than, or contemporaneous with, pyrite (see Figure 4).

Field relations and hand specimen examination suggest the bulk of mineralization took place during a single period. Ore microscopy studies frequently reveal cross-cutting relationships involving two or more sulfides, but these relationships are observed only on a very small scale (see Figure 5).

Some polished sections reveal numerous very small blebs of exsolved sphalerite within chalcopyrite. Edwards,¹⁴ has reported the exsolution of sphalerite within chalcopyrite takes place in the temperature range of 350°-400°C. This suggested temperature of exsolution corresponds well with the temperature of sulfide deposition suggested by fluid inclusion studies.

Secondary minerals observed in the area are; limonite,

chrysocolla, malachite, azurite, covellite, anglesite, pyrolusite and native copper. Although secondary minerals have been noted in diamond drill cores to depths of almost 100 feet, most of the secondary minerals, except the iron oxides, are seldom seen in the area.

In replacement zones quartz is usually the only non-metallic mineral present, but in sulfide-bearing veins quartz, muscovite and ankerite are the usual non-metallic minerals. Many vein specimens contain muscovite and ankerite in the central portion of the vein and it is with these minerals that sulfides are most frequently associated. This suggests that much of the sulfide deposition took place during the later stages of quartz deposition when muscovite, ankerite and sulfide were beginning to co-precipitate with quartz.

Some tension fractures reveal thin sulfide coatings, usually of chalcopyrite but occasionally of pyrite or pyrrhotite along margins of fractures with no associated non-metallic minerals.

Quartz veins most commonly are only sporadically mineralized, with high copper values in some places but very low copper values in other places. Silicified areas are usually of lower grade than mineralized portions of quartz veins, but are more consistent in copper content than the veins. In several areas mineralized quartz veins and silicified zones occur together.

Sporadic copper mineralization has been noted over an area of at least 6,000 feet x 3,000 feet. The present data is confined mainly to early results from diamond drilling concentrated in the area of the main showing. Within an area of 600' (minimum) x 200' (minimum) to depths of 400' or less, five diamond drill holes provided results ranging from 0.40% to 0.90% copper over true widths of 60 feet to 150 feet.

Similar copper values are reported for an area some 2,000 feet northeast of the main showing, but the dimensions of this mineralized area are not currently known.

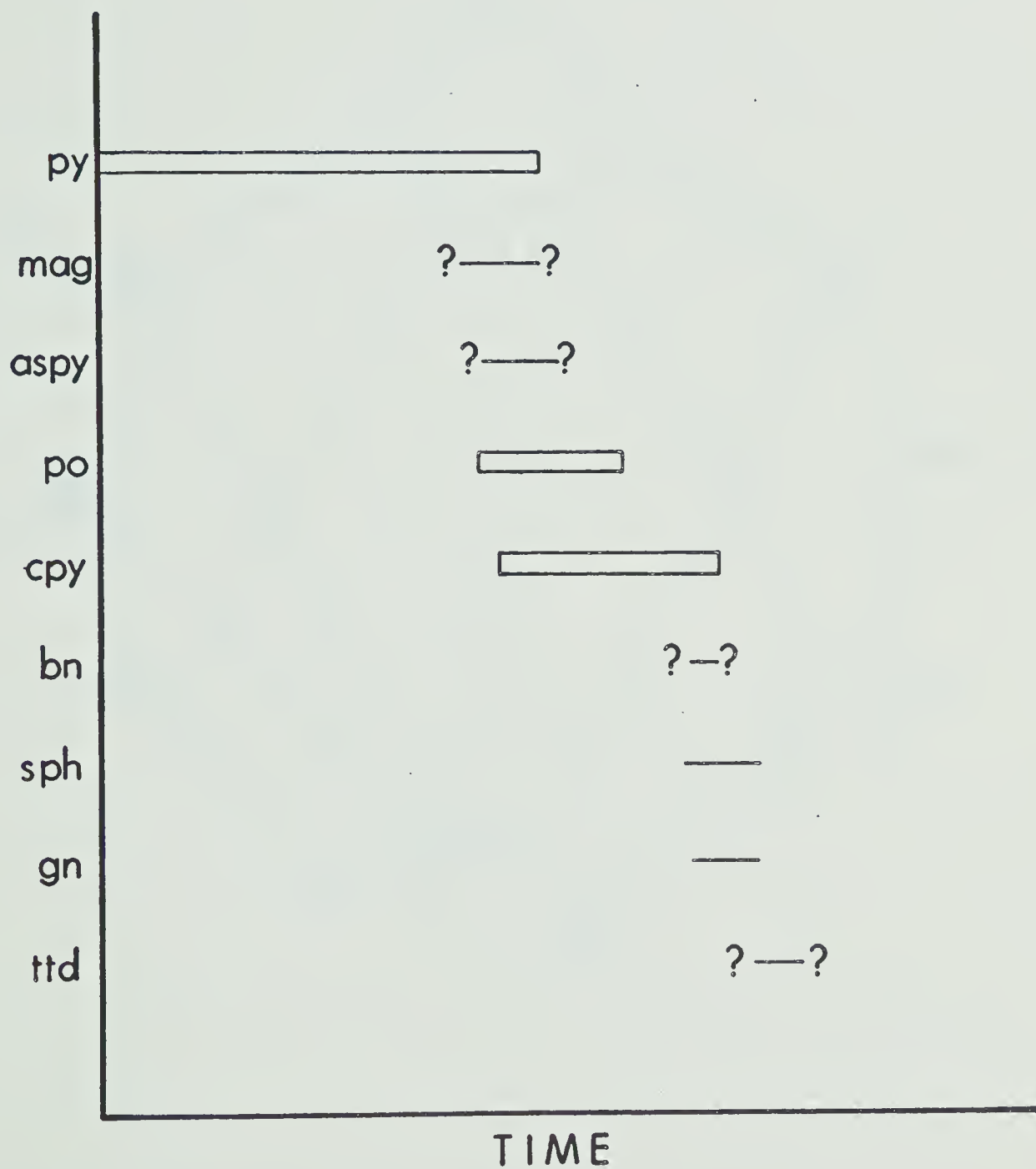


Figure 4 Sequence of Deposition of Primary Metallic Minerals, Noranda Creek, British Columbia.

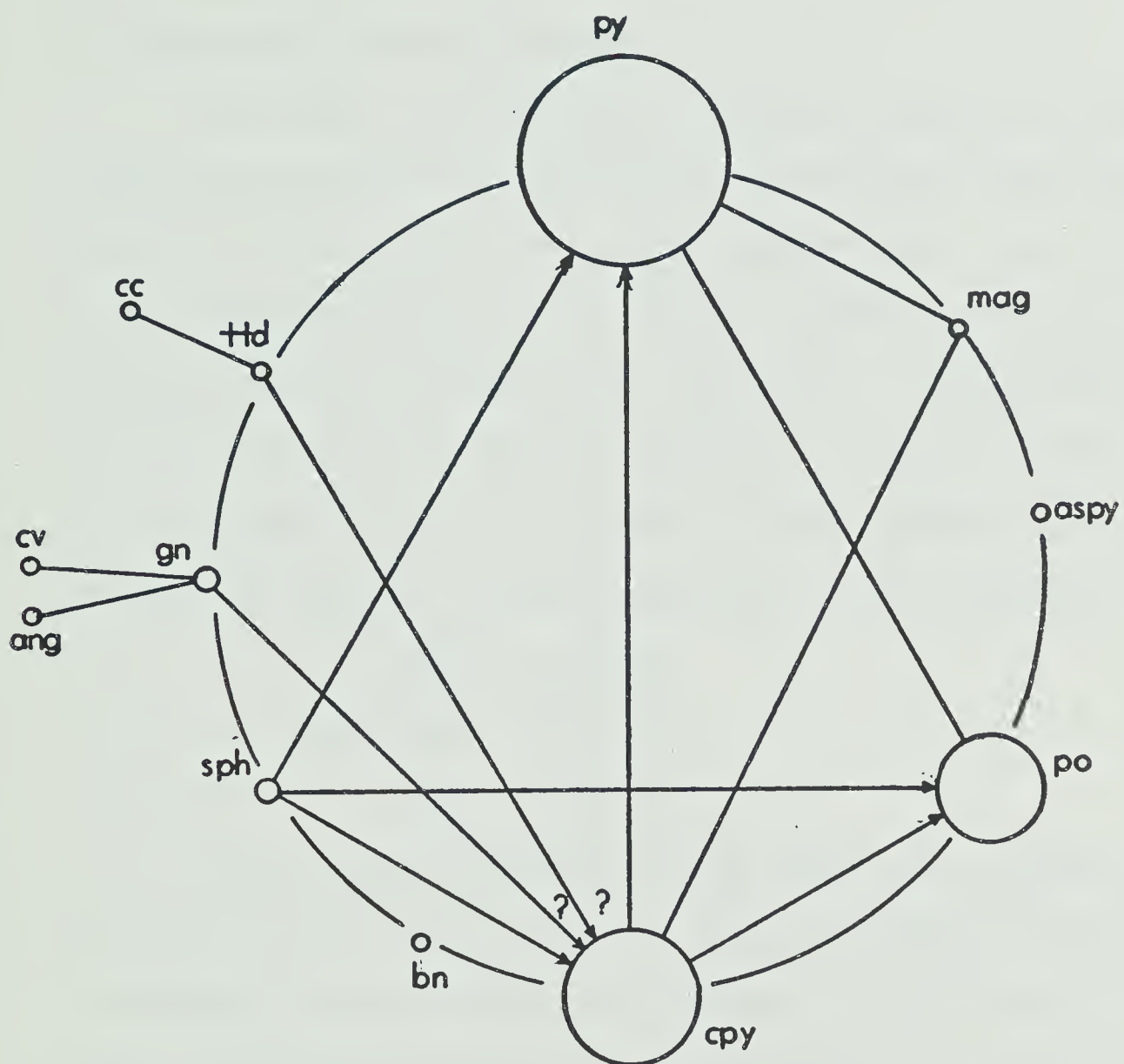


Figure 5 Van der Veen Diagram.

Chapter IV

FLUID INCLUSION DATA

A. Experimental Values Obtained

Six primary liquid-vapour inclusions in quartz from three sulfide-bearing quartz-carbonate-muscovite veins were individually heated on a heating state while being observed under a microscope. In the fluid inclusions observed, vapour phases occupied approximately 15-30% of the total volume of the inclusions. The temperature at which the two phase inclusion homogenized to a single, liquid, phase is the "homogenization" or "apparent filling" temperature. The values obtained for apparent filling temperatures in this study were:

235°C (1 value)

255°-260°C (3 values)

290°C (2 values)

Since all six inclusion-bearing samples were collected from the central portions of quartz veins which are less than 100 feet apart, it is unlikely that any significant temperature variation occurs between veins. A weighted average of the six homogenization values was calculated to be 265°C. Error introduced by inaccuracies in temperature measurement and visual observation is believed to be less than 20°C.*

*Dr. H. Ohmoto personal communication

B. Correction for Pressure

The homogenization or apparent filling temperature of the fluid inclusions would represent the true filling temperature if the pressure at the time of formation of the fluid inclusions was one atmosphere. Since this condition does not apply in most geological cases, a correction for pressure must be made. However, application of this correction factor requires; (a) an estimate of the salinity of the solution within the inclusion, and (b) an estimate of the total pressure existing at the depth at which the fluid inclusions were formed.

Roedder,³⁶ Ohmoto and Rye,³⁴ and others²² have shown that 5-10% (by weight) salt content is a typical range of salinities for solutions within fluid inclusions although values of greater than 30% salt content have been recorded. Data reported by Lemmlein and Klevtsov³¹ show very little difference in the pressure correction factor for pure water and a 30% salt solution at the same pressure. Therefore assumption of a 10% salt solution seems geologically reasonable and should provide a sufficiently accurate pressure correction factor to be of use in this study.

To estimate the pressure existing at the time of formation of the fluid inclusions it is necessary to know the pressure due to tectonic forces and the lithostatic pressure due to the weight of overlying rock units. Since there is no significant evidence of tectonic activity other than intrusion since Triassic-Jurassic time, in the present calculations total pressure will be taken as lithostatic pressure only.

Although no direct evidence of depth of emplacement of the Baldy Batholith is available, examples cited in several texts aid in estimating

the depth at which this intrusive body was emplaced. Barrell⁵ indicates the Late Cretaceous Maryville Batholith of Montana rose to within 4,000 feet of the earth's surface. Daly¹² has cited several works which suggest 2,000-20,000 feet as probable depths of emplacement for granitic intrusives. Shand⁴³ gives several examples of intrusions which are reported to have crystallized at depths of 2,000 to 6,000 feet below the earth's surface and states: "It is likely that in the case of all intrusions except perhaps the largest and most ancient batholiths, the pressure due to the weight of the roof did not exceed 1200 atmospheres in the upper part of the reservoirs...."

Calculations were carried out to determine the pressure correction applicable at depths considered to be the minimum, intermediate, and maximum probable depths of emplacement of the Baldy Granodiorite.

From the data of Lemmlein and Klevtsov³¹ (see Figure 6), for a solution containing 10% salt by weight, the pressure correction factors applied to fluid inclusions with apparent filling temperatures of 265°C were calculated for three depths of emplacement; 6,000 feet, 13,000 feet, and 20,000 feet.

a) Depth	6,000 feet
Pressure	600 bars
Temperature correction for pressure	55°C
Corrected filling temperature	320°C (265°+55°C)

b) Depth	13,000 feet
Pressure	1,300 bars
Temperature correction for pressure	125°C
Corrected filling temperature	390°C (265°+125°C)
c) Depth	20,000 feet
Pressure	2,000 bars
Temperature correction for pressure	195°C
Corrected filling temperature	460°C (265°+195°C)

The true filling temperatures of the fluid inclusions in these three cases, corrected for pressure, thus range from 320°C to 460°C. In the writer's estimation, since this relatively young intrusive has been exposed by erosion over an area of nearly 200 square miles, the lower and intermediate estimates of depth of emplacement are more geologically reasonable than the assumption of maximum depth. Therefore the true filling temperatures of the fluid inclusions in the sulfide-bearing veins at Noranda Creek were probably in the range of 320°C to 390°C.

If the assumption of no tectonic pressure is not valid the corrected filling temperatures for the inclusions observed will be higher than the range of 320°C-390°C. The magnitude of the difference in temperature between the true filling temperature and the range of temperatures determined in this study will depend upon the magnitude of the tectonic pressure. However, the observation of exsolved blebs of sphalerite within chalcopyrite in polished sections from the Noranda Creek area, a feature Edwards¹⁴ reported as occurring between 350°C and 400°C, suggests the temperatures indicated by fluid inclusion studies are geologically reasonable.

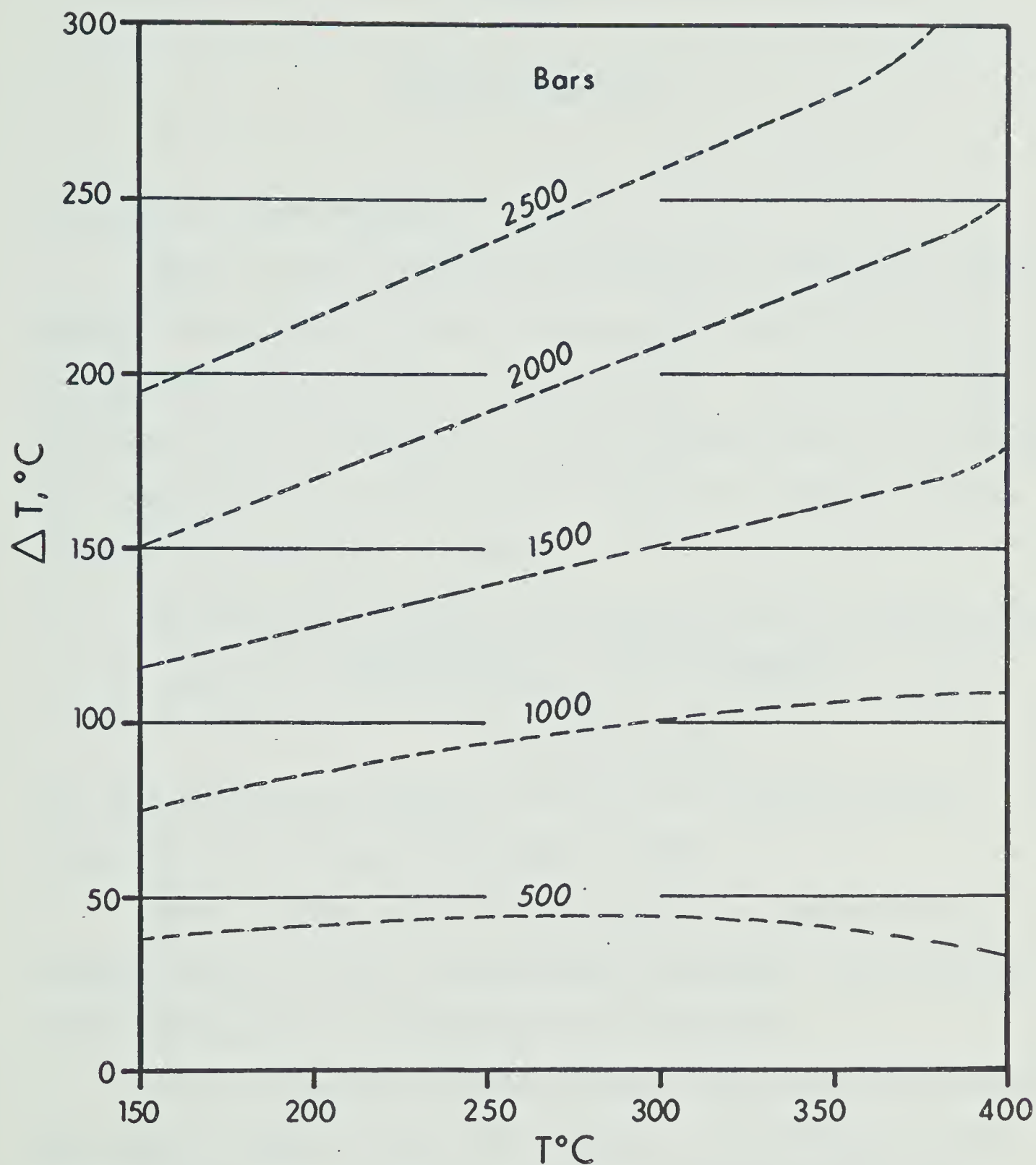


Figure6 Pressure Corrections for Temperature of Homogenization, after Lemmlein & Klevtsov (1961)

Chapter V

SULFUR ISOTOPE DATA

A. Isotopic Values Measured

Sulfur isotope analyses were completed on fifty-eight sulfide samples collected from outcrops, trenches, and diamond drill cores from an area of approximately 1.5 square miles. Sulfide samples were collected from all environments of sulfide mineralization, and analyses were completed on all sulfide species noted on the property with the exception of tetrahedrite and bornite

All values are reported in the standard (per mil) notation where

$$\delta S^{34}(\text{‰}) = \frac{S^{34}/S^{32}(\text{sample}) - S^{34}/S^{32}(\text{standard})}{S^{34}/S^{32}(\text{standard})} \times 1000$$

For this equation the standard is troilite from the Cañon Diablo meteorite which is taken to have $\delta S^{34} = 0.00\text{‰}$.

Sulfur isotope ratios for the standard and sample gas were compared using a 12", 90° Nier-type mass spectrometer. The precision of this instrument is considered to be ± 0.3 per mil.

Of the fifty-eight samples analysed, forty-seven had values in the range of -3.0‰ to $+6.0\text{‰}$ (see Figure 7). Of the eleven values outside of this range, three are more negative than -3.0‰ and eight are more positive than $+6.0\text{‰}$. The mean value for all analyses is 2.33‰ . If two analyses of samples from recrystallized limestone (galena $+11.02\text{‰}$,

sphalerite +12.13‰) are excluded, the mean value for fifty-six analyses is +2.00‰.

Table I. Sulfur Isotope Values for Various Sulfides from Noranda Creek, B.C.

<u>Mineral</u>	<u>No. of Analyses</u>	<u>Range of Values</u>	<u>Mean Value</u>
pyrrhotite	5	3.89‰	+4.34‰(all values)
pyrite	23	10.98‰	+3.70‰(all values)
sphalerite	3	11.83‰	+0.59‰(two values)*
galena	7	17.24‰	+0.24‰(five values)*
chalcopyrite	20	10.43‰	+0.13‰(all values)

*one sphalerite and two galena samples gave "anomalous" values which were not included in mean value calculations as their values would significantly displace the mean values of their respective sulfide averages.

Table II. Individual Sulfur Isotopic Values, Noranda Creek, B.C.

<u>Sample number</u>	$\delta S^{34}(\text{‰})$ values					<u>Rock Type</u>
	<u>py</u>	<u>po</u>	<u>cpy</u>	<u>sph</u>	<u>gn</u>	
K69-8-23-3			+1.45			silicified chlorite schist
K69-9-30-1(a)	+3.13					silicified phyllite
K69-9-30-1(b)	+3.46					silicified phyllite
K69-9-30-1(c)			+3.35			silicified phyllite
K69-9-30-2(a)	+3.64					silicified phyllite
K69-9-30-2(b)	+4.13					silicified phyllite
K69-10-1-6(a)		+2.81				quartz vein
K69-10-1-6(b)	+3.13					quartz vein
K69-10-5-3(a)	+9.82					disseminated in granodiorite
K69-10-5-5(a)			+1.44			silicified phyllite
K69-10-5-5(b)			+2.26			silicified phyllite
K69-10-5-5(c)1			-2.23			quartz vein
K69-10-5-5(c)2			-2.60			quartz vein
K69-10-5-5(c)3			-0.25			quartz vein
K69-10-5-5(d)1				+0.88		quartz vein
K69-10-5-5(d)2				-0.65		quartz vein
K69-10-5-5(d)3				+0.33		quartz vein
K69-10-5-5(e)			-2.80			quartz vein
K69-10-5-5(h)				-0.33		quartz vein
K69-10-5-5(i)				+0.46		quartz vein
K69-10-5-5(k)			+0.34			quartz vein
K69-10-5-5(m)			-2.44			quartz vein

<u>Sample Number</u>	<u>py</u>	<u>po</u>	<u>cpy</u>	<u>sph</u>	<u>gn</u>	<u>Rock Type</u>
K69-10-5-6(a)	+3.52					silicified phyllite
K69-10-5-6(b)		+3.22				silicified phyllite
K69-10-7-1(a)			+1.59			fracture coating
K69-10-7-1(b)			+2.43			fracture coating
K69-10-7-2	+0.83					quartz vein
K69-10-7-4			+1.82			silicified phyllite
K69-10-7-6(a)	+3.43					quartz vein
K69-10-7-6(b)	+3.21					quartz vein
K69-10-7-11	+4.03					quartz vein
K69-6-177	+4.70					disseminated in dyke
K69-12-248			+1.60			quartz vein
K69-13-235					+1.41	quartz vein
K69-17-308(a)		+5.61				dissem. in graphitic phyllite
K69-17-308(b)	+4.44					dissem. in graphitic phyllite
K69-22-27		+3.37				dissem. in graphitic phyllite
K69-22-171		+6.70				quartz vein
K69-22-206	+2.27					dissem. in phyllite
K69-22-316			+12.13			fracture in limestone
K69-24-395(a)	+0.34					quartz vein
K69-24-395(b)			+1.30			quartz vein
K70-10-2-8(a)	+2.71					disseminated in quartzite
K70-10-2-8(b)	+0.38					quartz vein
K70-10-2-8(c)	+0.84					quartz vein
K70-10-2-8(d)			+0.26			quartz vein

<u>Sample Number</u>	<u>py</u>	<u>po</u>	<u>cpy</u>	<u>sph</u>	<u>gn</u>	<u>Rock Type</u>
K70-10-2-11	+7.78					silicified phyllite
K70-10-2-12	+6.16					silicified phyllite
K70-10-2-14	+8.44					disseminated in quartzite
K70-10-2-17(a)	+6.20					disseminated in quartzite
K70-10-2-17(b)			+5.73			quartz vein
K70-10-2-23				+0.30		quartz vein
K70-10-11-1					+11.02	disseminated in limestone
K70-35-354(a)	-1.16					quartz vein
K70-34-354(b)			-3.04			quartz vein
K70-37-507(a)					-6.22	quartz vein
K70-37-507(b)			-4.69			quartz vein
K70-48-181			+2.84			quartz vein



Figure 7 δS^{34} analyses from Noranda Creek Area, British Columbia.

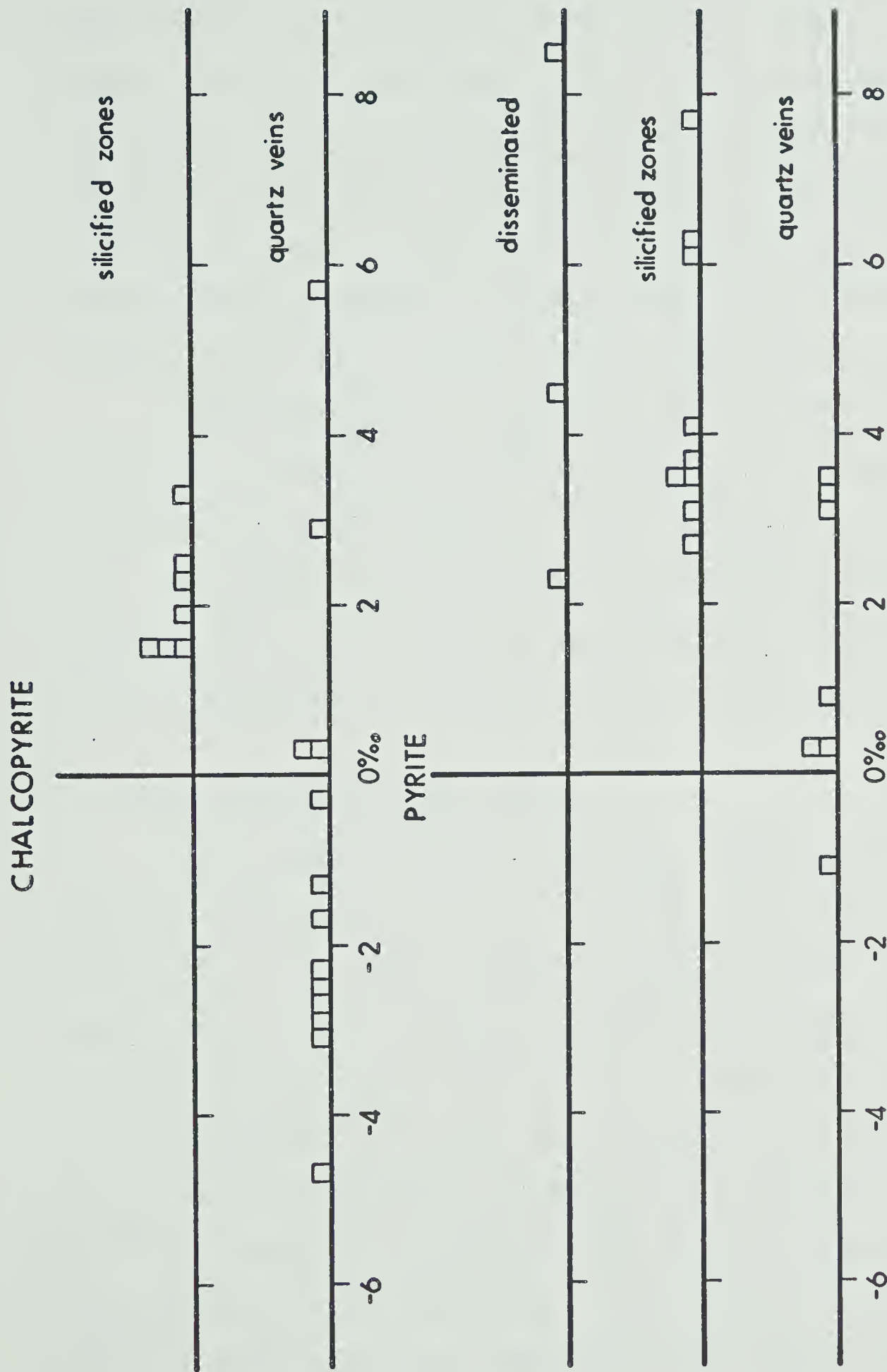


Figure 8 Relationship of δS^{34} Values to Environment of Deposition for Pyrite and Chalcopyrite, Noranda Creek Area, B.C.

Samples of pyrite, chalcopyrite, galena and sphalerite from quartz-ankerite veins and silicified zones in the vicinity of the main copper showing gave values in the narrow range of +2.26‰ to -2.80‰. However, when values from samples distant from the main showing are considered, the range of analytical values becomes much larger (see Figure 7). This increase in the overall range of analytical values is partly due to changes in physico-chemical conditions (pH and oxygen fugacity) when hydrothermal solutions encountered metamorphosed limestone and partly due to sulfur isotope zonation around the Baldy Batholith.

Samples K70-10-11-1, a galena with δS^{34} of 11.02‰, and K70-22-316, a sphalerite with δS^{34} of 12.13‰ were collected from a re-crystallized graphitic limestone, a minor lithology noted in the thesis area. The chemistry of this lithology is significantly different from other lithologies in the area, and it is likely the chemistry of this unit is responsible for the highly positive sulfur values.

B. Trends in Measured Isotopic Values

Pyrite samples K70-10-2-11 (+7.78‰), K70-10-2-12 (+6.16‰), K70-10-2-14 (+8.44‰) and K70-10-2-18 (+6.20‰) have values in the order of 3 per mil or more above the mean δS^{34} value for pyrite. These samples were the most southerly (proximal to the Baldy Batholith) collected by the writer and reflect the trend in sulfur isotope zoning around the Baldy Granodiorite. δS^{34} values are most positive near the Baldy intrusive and become progressively more negative (corresponding to a depletion in S^{34} or conversely an enrichment in S^{32}) the more distant one samples from the intrusive (see Figure 10). Pyrite sample K70-35-354(a) with δS^{34} of -1.16‰ is the pyrite sample most distal from the intrusive and

has the most negative value for any pyrite collected in this survey.

Chalcopyrite, like pyrite, reveals a sulfur isotope zonation within the thesis area. Sample K70-10-2-17(b) with δS^{34} value of +5.73‰ was the most southerly chalcopyrite collected and has the most positive δS^{34} value. Chalcopyrite samples from the central region of the thesis area have values in the approximate range of -2.50‰ to +2.50‰, while sample K70-37-507(b) with a value of -4.69‰ was the most northerly chalcopyrite collected (see Figure 11).

Since galena was much less abundant in the area than pyrite or chalcopyrite, only limited data are available on sulfur isotope values from this sulfide. Excluding the value of sample K70-10-11-1 (+11.02‰) which can be explained on the basis of chemical conditions within limestone, six values for galena range from -6.22‰ to +1.41‰. Five of these six values are in the range of -0.65‰ to +1.41‰. This range of 2.06 per mil is from samples collected within a radius of some 100'-150'. Among these samples, no trend in sulfur isotope values was noted. However, sample K70-37-507(a) with a value of -6.22‰ was collected approximately 2,200 feet northeast of the other five galena samples. This decrease in S^{34} content follows the pattern of more negative sulfur isotope values in the northern part of the thesis area, but since data on galena are scarce, other explanations for this very negative galena value cannot be ruled out.

On a more local scale it was observed that, with the exception of K70-10-2-17(b), a sample collected from the southernmost region of the property, chalcopyrite from quartz-carbonate-muscovite veins was consistently negative or very slightly positive (values -4.69‰ to +0.34‰) whereas chalcopyrite occurring as disseminated grains, coating

fractures or from silicified zones was consistently positive with values ranging from +1.82‰ to +2.43‰ (see Figure 8).

Pyrite samples K69-10-5-3(a) with δS^{34} of 9.82‰ and K69-6-177 with δS^{34} of +4.70‰ are the only sulfide samples taken from intrusive rocks within the thesis area. K69-10-5-3(a) is a sample of the sheared and partly altered granitic (quartz diorite ?) rock exposed in the bottom of Noranda Creek at an elevation of approximately 4,800' above sea level. K69-6-177 is a sample of diabase dyke from diamond drill core obtained in the vicinity of the main showing.

Sample K69-22-316, a sphalerite with δS^{34} of +12.13‰ and sample K70-10-11-1, a galena with δS^{34} of 11.02‰, both occur within metamorphosed graphitic limestone. These two specimens produced the "heaviest" sulfur isotopic values of all the samples analyzed during this study. Beales and Jackson⁶ noted sulfides in carbonates in the Pine Point lead-zinc deposits had S^{34} values averaging approximately +18‰. They suggested the very positive isotopic values may represent sulfur from H_2S within the carbonate rather than sulfur of magmatic hydrothermal origin. A similar explanation can be offered for these two samples from Noranda Creek.

C. Interpretation of Sulfur Isotope Values

With the exception of several explainable "anomalous" values, the sulfur isotope analyses in this study fall within the range of -3.0‰ to +6.0‰. Jensen²⁵ has suggested this narrow range of values indicates a magmatic hydrothermal source for the sulfides. His studies show that deposits of metamorphic hydrothermal origin have δS^{34} values ranging from -30‰ to +18‰, while ground water hydrothermal deposits range

from approximately 0‰ to -44‰. In contrast Jensen's values for magmatic hydrothermal deposits range from -6‰ to +10‰, a narrow range when compared with the values of metamorphic hydrothermal and ground water hydrothermal deposits.

In a more recent publication, Jensen²⁷ states: " δS^{34} analyses of sulfides in Cordilleran intrusives exhibit near zero per mil values indicative of primordial sulfur derived from the upper mantle, but possibly derived from the lower crust."

The range of sulfur isotope values from the Noranda Creek area and their proximity to the meteoritic value of 0‰ correspond closely to the values for magmatic hydrothermal deposits which Jensen has cited, and it appears likely that the sulfides in the Noranda Creek area are of magmatic hydrothermal origin.

Several workers have reported a pattern of sulfur isotope zonation around intrusive bodies. S^{34} is frequently enriched in sulfides within or near the intrusive, while S^{32} enrichment (or S^{34} depletion) is more characteristic of sulfides which have been deposited at a distance from the intrusive. Although some exceptions do occur, the general pattern is one of decreasing S^{34} content corresponding to increasing distance of the sulfide from the intrusive. On a smaller scale, Jensen and others have noted sulfur isotope differences between vein sulfides and associated wall rock sulfides. S^{32} is typically enriched in wall rock sulfides, S^{34} enriched in vein sulfides. Field,¹⁵ in a study of sulfur isotope zoning within the Bingham Stock, Utah, found a zoning pattern in that area similar to the pattern observed at Noranda Creek. He noted that the sulfur isotope zoning pattern was three dimensional at Bingham,

both within the copper sulfides in the intrusive and within the lead-zinc deposits peripheral to the Bingham Stock. Insufficient data are presently available from the Noranda Creek area to see if any vertical zoning is expressed in sulfur isotope ratios. In a 1966 publication Field¹⁵ suggested a diffusion mechanism was at least partly responsible for the observed zoning pattern. At that time he suggested S^{32} would diffuse away from an intrusive more rapidly than S^{34} . This preferential diffusion would result in a zone of relative enrichment of S^{34} near the intrusive, while S^{32} would be relatively enriched beyond the zone of S^{34} enrichment. Both, et al.⁷ noted S^{34} zonation as well as mineralogical zoning around a granite stock in Tasmania. Like Field, Both, et al. ascribed to a diffusion mechanism to explain the observed sulfur isotope zonation.

Bachinski,⁴ Field,¹⁵ and Both, et al.⁷ also considered precipitation of S^{34} -rich sulfides near the intrusive as a possible cause of sulfur isotope zonation. Precipitation of S^{34} -rich sulfides near the intrusive would deplete hydrothermal solutions in S^{34} . Thus sulfides which crystallized at a distance from the intrusive would be precipitating from a solution which contained a lower concentration of S^{34} and the sulfide would reflect this relative depletion of S^{34} . This mechanism would suggest the occurrence of sulfur isotope exchange reactions and would indicate more or less contemporaneous sulfide deposition.

Field and Moore¹⁶ noted the common trend of S^{34} depletion with increasing distance from an intrusive body in their study of the U.S. Mine, a lead-zinc deposit peripheral to the Bingham Stock, Utah. Their explanation for the zoning was pH change within the hydrothermal solution, rather than a diffusion mechanism or uptake of S^{34} in near-

intrusive sulfides. Lange and Cheney,³⁰ in another 1971 publication also invoked change in pH of the hydrothermal solutions at Butte, Montana, to explain their apparent "reversed" zoning pattern in which sulfides are isotopically heavier the more distant they are from the main zone of mineralization.

As shown by Sakai³⁹ the dominant sulfur-bearing species within hydrothermal solutions depends upon the pH of the hydrothermal system. H_2S is the dominant sulfur species in acidic solutions, HS^- the major species in weakly alkaline solutions, and $S^{=}$ the main sulfur species in alkaline solutions. Since each of these species has a different fractionation factor, the sulfur isotope composition of each of these three species will be different even though temperature and pressure conditions may be the same. This inherent fractionation within these sulfur species will produce different sulfur isotopic values in sulfide precipitates. Thus the apparent fractionation within a suite of sulfide minerals may, at least partially, represent isotopic fractionation inherited from the appropriate sulfur species within the mineralizing solution. Therefore a change in pH of the hydrothermal solution may influence the relative abundances of H_2S , HS^- and $S^{=}$. If there is a change in the relative abundances of H_2S , HS^- and $S^{=}$ due to a change in pH, sulfides of different isotopic composition may be formed even though most geologic parameters remain unchanged.

The papers of Field and Moore,¹⁶ and Lange and Cheney³⁰ indicate pH change within the hydrothermal solutions can produce results similar to those suggested for diffusion processes. Wall rock reactions could produce sufficient pH change in the solutions to cause a change in the most abundant sulfur species thus causing significant differences in

sulfur isotope values. Therefore the change in isotopic composition of vein sulfides compared to wall rock sulfides would depend upon the nature of wall rock reactions and their effect upon the pH of the hydrothermal solutions. Different reactions would produce different pH changes and thus different isotopic variations between vein sulfides and associated wall rock sulfides.

Another possible explanation for the isotopic zoning across the thesis area is isotopic fractionation between sulfate and sulfide species. S^{34} is typically enriched in sulfate minerals compared to associated sulfides. Several workers have obtained values of +5‰ to +25‰ for barite associated with mineral deposits in which sulfides have negative values. As indicated by Sakai³⁹ (page 45) formation of isotopically "heavy" sulfate species in solution would deplete the amount of S^{34} available in solution for sulfide formation, thus causing sulfides to become isotopically "lighter" (enriched in S^{32}). This mechanism could explain the isotopic zonation pattern noted at Noranda Creek and other areas. Since sulfate minerals are usually found in moderate to low temperature environments, it is likely sulfate species formed in the Noranda Creek area have crystallized outside of the mineralized areas in cooler surroundings, thus explaining the absence of barite or other sulfates within the thesis area. Since the presence of sulfate species outside the thesis area has not been tested, at this time the writer can neither confirm nor deny this mechanism of isotopic fractionation between sulfate and sulfide as a possible cause of the observed isotopic zonation pattern.

Vein chalcopyrite at Noranda Creek consistently was found to be isotopically lighter than chalcopyrite in associated siliceous zones.

Several workers, including Field,¹⁵ and Field and Moore¹⁶ have found vein sulfides to be typically heavier than associated wall rock sulfides while Lange and Cheney³⁰ have reported several wall rock pyrite samples which are isotopically heavier than pyrite from associated quartz veins.

The "heavy" vein sulfides and "light" wall rock sulfides were explained by a diffusion mechanism, the wall rock sulfides forming by lateral secretion of metal ions and sulfur ions from the open vein. With S^{32} diffusing from the intrusive more rapidly than S^{34} , the earliest sulfur which diffused into the wall rock would be enriched in S^{32} . Later, when essentially all diffusion out of the open vein had ceased due to filling of all pore space in the host rock by quartz and sulfides, the hydrothermal solutions would possess a higher S^{34}/S^{32} ratio than at the time of initial diffusion. This increase in the S^{34}/S^{32} ratio would be due to the slower diffusing S^{34} finally reaching the area of mineralization after the earlier, S^{32} has passed through the mineralized zone or had been trapped as a sulfide phase.

At Noranda Creek the most probable explanation for sulfur isotopic zoning is precipitation of S^{34} enriched species near the intrusive, thus depleting the amount of S^{34} remaining in hydrothermal solution.

The mechanism of isotopic diffusion would produce "light" wall rock sulfides and relatively "heavy" vein sulfides. This pattern is the reverse of the pattern found at Noranda Creek so the diffusion mechanism is not believed responsible for the overall sulfur isotope pattern found within the thesis area.

The change in pH of hydrothermal solutions is not accepted as a major factor in sulfur isotope zoning at Noranda Creek since pH

change should be reflected in a change of vein or wall rock mineralogy but no such mineralogical change was observed in the area.

The observed sulfur isotope trends at Noranda Creek are not without anomalies, and it is suggested the discordant values may be the result of localized processes which produced isotopic ratios which are not consistent with the main mechanism which was in effect.

The mean of the δS^{34} values for various sulfides analyzed in this study approach the theoretical equilibrium sequence calculated by Sakai³⁸ and numerous other workers. Bachinski⁴ has explained this equilibrium sequence on the basis of bond strengths, the strongest bonds being in those sulfides which show the greatest enrichment in S^{34} . According to Bachinski, the measured and inferred relative bond strengths are; $py > po > sph > cpy > gn$. This sequence is a duplicate of the equilibrium sequence calculated by Sakai and others.

D. Sulfur Isotope Temperature Determination

When this study was begun it was expected from field evidence that various pairs of co-existing sulfides would exhibit textures indicating co-precipitation of the mineral pairs. This evidence of sulfide-sulfide equilibrium would have enabled the writer to use the magnitude of sulfur isotope fractionation between sulfide species to calculate the temperature of deposition of the sulfides, as suggested by Sakai and numerous other workers. However, examination of a number of polished sections revealed numerous, small scale, cross-cutting relationships involving all of the more abundant sulfides, thus destroying the assumption of co-precipitation of sulfides. Analyses of a few co-existing pairs of sulfides reveal that, although cross-cutting relations do exist between

the pair, the isotopic analysis corresponds to the equilibrium sequence noted by other workers. This indicates near equilibrium conditions were attained even though cross-cutting relations are observed.

$\Delta\delta S^{34}$ values for several sulfide pairs which showed only minor cross-cutting relationships were plotted on a graph of amount of isotopic fractionation versus temperature of deposition (after Kajiwara and Krouse²⁹).

Table III. Apparent Temperatures of Deposition Using the "Sulfur Isotope" Geothermometer

<u>Sample Number</u>	<u>Sulfide Pair</u>	<u>$\Delta\delta S^{34}$ (‰)</u>	<u>T, °C</u>
K69-17-308	py-po	1.17	240
K69-10-5-5(d)	gn-sph	1.53	450
K70-37-507	cpy-gn	1.53	380
K69-24-395	py-cpy	1.64	260
K70-35-354	py-cpy	1.88	220
K70-10-2-17	py-cpy	0.47	660

As shown in Table III and Figure 12, the resulting temperature values range over approximately 400°C. Since it is unlikely such a drastic range of temperature did exist within the area at the time of sulfide mineralization, the method of temperature determination by means of sulfur isotope fractionation measurements is suspect in this study. Possible reasons for the large apparent differences in temperature are numerous and include:

- a) lack of complete equilibrium between sulfides
- b) impurities in samples, i.e. exsolution blebs
- c) comparison of results from different sulfide pairs
- d) experimental error in gas analysis
- e) experimental error in reference graph.

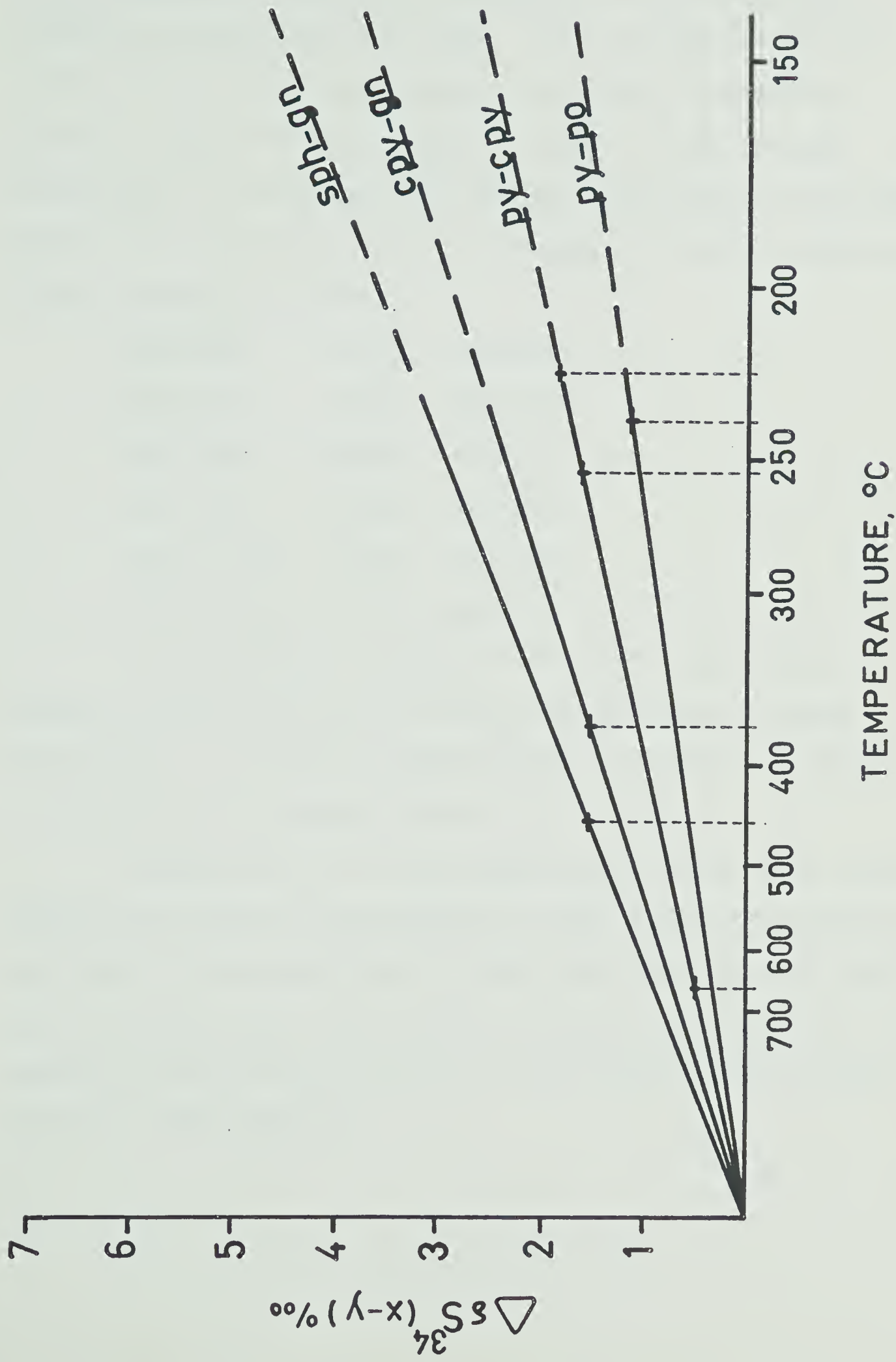


FIGURE 12 ISOTOPE TEMPERATURES,

NORANDA CREEK, B.C.

(Kajiwara and Krouse)

Although the range of temperature values is large and the values are not completely consistent, in a general way the values show a temperature gradient across the area. If the locations of the six sulfide pairs on which the temperature measurements were made are plotted on a map, the values exhibit a pattern of lower "isotope temperatures" to the north, higher "isotope temperatures" to the south (nearest the Baldy Granodiorite). The sequence of "isotope temperature" values from north to south is:

K70-37-507	380°C	(cpy-gn)
K70-35-354	220°C	(py-cpy)
K69-17-308	240°C	(py-po)
K69-24-395	260°C	(py-cpy)
K69-10-5-5(d)	450°C	(gn-sph)
K70-10-2-17	660°C	(py-cpy)

The most northerly sample pair (K70-37-507) gives the only temperature value which does not agree with the trend of "isotope temperatures". At present insufficient data are available to suggest a reason for this "anomalous" value.

Although at this time only generalizations can be made regarding temperatures obtained by measurements of sulfur isotope fractionation, this aspect of the study deserves further work. More extensive sample collection and analysis could provide a clearer overall picture of the temperature during mineralization and of the causes of local isotopic variations within the area.

Chapter VI

RADIOMETRIC DATA

A. Results Obtained

Two biotite samples from the Baldy Granodiorite and two muscovite samples from narrow, sulfide-bearing, quartz-carbonate-muscovite veins were collected for potassium-argon age determinations. The biotite samples were collected approximately two miles south of the thesis area, a mile or more within the border of the batholith. One muscovite sample (K70-10-2-22) was collected in the vicinity of the main mineralized zone, in the central region of the thesis area. Muscovite sample K70-10-2-16 was collected in the southeastern part of the area, approximately 4,500 feet south of muscovite sample K70-10-2-22.

The two samples of biotite from the Baldy Batholith gave ages of 98 m.y. and 103 m.y. These dates correspond well with a date of 96 ± 5 m.y. obtained by the Geological Survey of Canada from a biotite sample collected approximately six miles southwest of the thesis area.¹⁸ Muscovite samples K70-10-2-16 and K70-10-2-22 gave apparent ages of 110 m.y. and 140 m.y. respectively. The limit of error in all of these measurements is believed to be $\pm 5\%$.*

*Dr. H. Baadsgaard personal communication

Table IV. K-Ar Age Determinations, Noranda Creek, B.C.

<u>Sample</u>	<u>Rock Type</u>	<u>Mineral</u>	<u>%K₂O</u>	<u>Ar⁴⁰/K⁴⁰</u>	<u>Apparent Age</u>
K69-11-5-2	granodiorite	biotite	7.53	0.006218	103 m.y.
K69-11-5-7	grabodiorite	biotite	7.35	0.005908	98 m.y.
K70-10-2-16	quartz vein	muscovite	8.51	0.006702	110 m.y.
K70-10-2-22	quartz vein	muscovite	7.96	0.008490	140 m.y.

$$\lambda_e = 0.585 \times 10^{-10}/\text{year} \quad \lambda_\beta = 4.72 \times 10^{-10}/\text{year}$$

$$K^{40}/K = 0.000119$$

B. Interpretation of Radiometric Data

Field relations suggest sulfide mineralization was probably associated with intrusion of the Baldy Granodiorite. The apparently older ages of the muscovite compared to biotite may be due to the contamination of radiogenic argon from sericitic quartzite country rock which is cross-cut by mineralized quartz veins.

There is no reason to believe the muscovite-bearing veins are pre-Baldy Batholith. The high fluid inclusion temperatures suggest the veins formed quite near an intrusive body, but there is no evidence whatsoever for an older intrusion anywhere in the vicinity of the thesis area. It appears more likely that contamination of radiogenic Ar⁴⁰ derived from sericitic quartzite host rock is responsible for the older apparent ages obtained from vein muscovite, and that the true age of these mineralized veins is approximately the same as the age of the Baldy Granodiorite. Numerous workers^{10,11,23} have suggested the presence of excess radiogenic argon is due to contamination and Curtis¹⁰ has stated "...it appears that contamination from old potassium-bearing minerals is a far more likely cause of excess radiogenic argon in samples than

argon left in the magma at the time of eruption....". At the present time the most reasonable explanation for the older muscovite ages appears to be contamination from older argon-bearing minerals.

Chapter VII

SUMMARY

A study was conducted on several aspects of sulfide deposition in an area of pyrite-chalcopyrite mineralization in southern British Columbia.

Host rocks are an assemblage of quartzites and acidic to basic phyllites and schists believed to be of late Paleozoic age. These units were metamorphosed to the upper greenschist facies during the Shuswap Metamorphic event which occurred in the late Paleozoic and early Mesozoic.

The metamorphic rocks in the vicinity of the thesis area have been intruded by a mid-Cretaceous granodiorite batholith which presently is exposed over an area of almost two hundred square miles. This batholith represents the southeasternmost end of a trend of mid-Cretaceous intrusives of intermediate composition which are exposed semi-continuously along a northwest-southeast trend approximately sixty miles in length.

Pyrite, pyrrhotite, chalcopyrite and small amounts of galena, sphalerite, arsenopyrite, bornite and tetrahedrite are present in the area. These sulfides occur primarily as finely disseminated grains, in silicified zones, or in quartz veins while small amounts of pyrite, pyrrhotite and chalcopyrite were observed as open fracture coatings.

Examination of hand samples and polished sections has shown some

cross-cutting relations on a very small scale, but megascopically cross-cutting relations are rare. The apparent sequence of sulfide deposition as deduced from hand specimens and polished sections was:

- (1) pyrite
- (2) arsenopyrite
- (3) pyrrhotite
- (4) chalcopyrite
- (5) bornite
- (6) sphalerite
- (7) galena
- (8) tetrahedrite

Six liquid-vapour inclusions in quartz collected from several sulfide-bearing veins have produced apparent filling temperatures of approximately 265°C. On the assumption of a depth of emplacement of 6,000-13,000 feet and a 10% salt content in the fluid within the inclusions, filling temperatures corrected for pressure ranged from approximately 320° to 390°C.

Fifty-eight analyses of sulfur from five sulfide species; pyrite, pyrrhotite, chalcopyrite, galena and sphalerite produced sulfur isotope values ranging from -6.22‰ to +12.13‰ with a mean of +2.33‰.

Pyrite, chalcopyrite, and to some extent galena, revealed a pattern of sulfur isotope zoning with S^{34} being enriched near the intrusive and progressively depleted the farther one travels from the granodiorite. This zonation is most probably due to depletion of S^{34} in hydrothermal solutions due to deposition of S^{34} enriched phases such as pyrite and pyrrhotite near the intrusive, but other explanations such as diffusion, pH change and formation of "heavy" sulfate are possible and further work is necessary to determine the most likely explanation for the observed isotopic zoning around the Baldy Batholith.

Chapter VIII

CONCLUSIONS

On the basis of data collected during this study the following conclusions may be drawn:

- 1) Sulfide mineralization occurred during one main period of deposition although minor cross-cutting relations may be observed in some polished sections.
- 2) Sulfide-bearing replacement zones and some mineralized veins closely follow cleavage, suggesting the cleavage developed during the Shuswap metamorphic event may have provided some channels for movement of hydrothermal solutions.
- 3) Thin section and polished section work indicate most vein sulfides crystallized contemporaneously with carbonate and muscovite after the bulk of vein quartz had precipitated.
- 4) Fluid inclusion work suggests the temperature of sulfide deposition was in the range of 320°-390°C, in good agreement with the temperature suggested by the exsolution of sphalerite within chalcopyrite (350°-400°C).
- 5) The relatively narrow range of analytical values and the near meteoritic sulfur isotope values for sulfides from Noranda Creek suggest the sulfur was derived from a homogeneous source, possibly the upper mantle or lower crust. The Baldy Granodiorite is the most

likely source of sulfur because an intrusive of mantle or lower crustal origin would provide near meteoritic sulfur values similar to those obtained for Noranda Creek sulfides.

- 6) Sulfur isotope values for various sulfides approach the equilibrium sequence of S^{34} enrichment predicted by theoretical calculations, but the lack of complete conformity to the equilibrium sequence indicates that although equilibrium was approached, it was not attained.
- 7) Considering the data presently available from Noranda Creek, the most probable explanation for the observed trend in isotopic zoning, with sulfides near the intrusive being isotopically "heavier" than more distant sulfides, is depletion of S^{34} in hydrothermal solutions due to uptake of the heavier isotope in near-intrusive sulfides. Diffusion processes and change in pH of the hydrothermal solutions were probably responsible for local variations in isotopic values. Formation of isotopically heavy sulfate may have had an effect on the zoning pattern, but at present insufficient data are available to properly evaluate the significance of this mechanism.
- 8) Potassium-argon determinations indicate the Baldy Batholith was emplaced approximately 100 m.y. ago.
- 9) The Baldy Batholith Granodiorite was probably emplaced in an epizonal environment at depths in the order of 6,000-13,000 feet below the Earth's surface.
- 10) The similarity of age and composition of the Baldy Granodiorite and the Boss Mountain Quartz Diorite suggest the two intrusives may be genetically, as well as chronologically, related.

- 11) Dykes in the vicinity of the main showing were emplaced along cleavage planes after mineralization had occurred, as indicated by the lack of alteration, veining or mineralization within the dykes. These bodies probably represent the last phases of intrusion in the area.
- 12) The ages determined by K-Ar analyses on vein muscovites are older than results from biotite of the Baldy Granodiorite. There is no evidence that the veins are older than the granodiorite, and it is concluded the older ages do not represent the time of formation of the muscovite, but are due to contamination of radiogenic argon from the older, sericitic quartzite host rock.

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APPENDIX A

Sample Preparation for K-Ar Extraction Procedure

1. Rock sample crushed to -35 mesh.
2. Sample sieved 35-60-140-200 mesh.
3. Heavy liquid separation
 - (a) each muscovite fraction immersed in acetone-tetrabromoethane mixture with specific gravity low enough to sink muscovite but float quartz, carbonate and feldspars
 - (b) each biotite fraction immersed in pure tetrabromoethane (S.G.~3.0) to sink biotite (+hornblende, sphene, oxides, sulfides) but float muscovite, quartz, feldspars and carbonates

Heavy fractions washed six times with acetone

4. Magnetic separation
 - heavy fraction from each sieve fraction checked with hand magnet (magnetics discarded)
 - non-magnetic fraction run on Frantz Isodynamic Separator
 - (a) Muscovite
 - heavy fraction run at 0.2A magnetics discarded
 - 0.5A " "
 - 0.7A " "
 - 1.0A " "
 - 1.2A " "
 - 1.5A " "
 - 1.7A non-magnetics retained
 - (b) Biotite
 - heavy fraction run three times at 0.2A (magnetics discarded)
 - then three times at 0.5A (magnetic fraction retained)

5. Samples checked under binocular microscope for purity

- (a) muscovite samples: >95% pure fresh muscovite with 3% iron stained muscovite and 1% quartz-sulfide grains
- (b) biotite samples: 95% fresh biotite with 1% sphene, 1% hornblende and 3% weakly chloritized biotite.

APPENDIX B

Potassium Analysis

1. 0.25 gram sample weighed into platinum dish.
2. Sample moistened with distilled H_2O then 3 ml of 1:1 H_2SO_4 + 5 ml HF were added.
3. Sample evaporated to dryness then ignited, first over a bunsen burner then over a meker burner for one hour.
4. Residue moistened with 10 ml H_2O and solution transferred to 50 ml beakers.
5. Sample leached on steam bath for 30 minutes, decanted through 7 cm blue filter paper then leached two more times with 10 ml volumes for 15 minutes. Solution filtered into 150 ml beaker.
6. Residue transferred to paper and washed three times with hot H_2O .
7. Residue transferred back to platinum dish, 2 ml 1:1 H_2SO_4 added and operation repeated beginning at step 3.
8. Solution heated to $50^\circ C$ and potassium precipitated with sodium tetraphenol boron (20 mg/ml).
9. Precipitate allowed to stand for two hours, then filtered through fine fritted filters. Filter then washed with 2% sodium tetraphenol boron solution and then three times with cold distilled H_2O .
10. Precipitate dried at $110^\circ C$ for one hour, sample weighed and $\%K_2O$ reported.

APPENDIX C

Sample Preparation for Sulfur Isotope Extraction Procedure
(for sulfides too fine-grained to be hand picked)

1. Sample crushed to -60 mesh.
2. Sample sieved 60-140-200 mesh.
3. Heavy Liquid Separation
 - 140 to 200 mesh fraction immersed in pure tetrabromoethane
 - heavy fraction examined for presence of pyrite
 - (a) if pyrite present, extraction was continued
 - (b) if pyrite absent, extraction was discontinued
 - for samples containing pyrite the 60-140 and -200 mesh fractions were immersed in tetrabromoethane and the heavy fraction extracted
 - each heavy fraction washed six times with acetone
4. Magnetic Separation
 - each fraction checked with hand magnet (magnetics discarded)
 - samples run on Frantz Isodynamic Separator

0.2A	magnetics	discarded
0.5A	"	"
1.0A	"	"
1.2A	"	"
1.5A	"	"
1.7A	non-magnetics	retained
 - the non-magnetic fraction, usually >95% pyrite was crushed to -100 mesh and retained for sulfur isotope work

APPENDIX D

SO₂ Gas Preparation

Two methods of SO₂ gas generation were utilized in this study. In one method 100 μ g CuO powder and 10 μ g metallic sulfide powder were intermixed and burned at 1000°C for 5 minutes. In the second method 10-20 μ g of metallic sulfide powder were burned at 1200°C for five minutes in a direct flow of pure oxygen.

After combustion, gas purification, collection and analysis procedures were essentially the same for both methods.

Analyses of several specimens by both methods gave differences of 0.2‰ or less.

Working standard used was YKS-GM1A, a pyrrhotite from the Giant Mascot Mine, British Columbia with δS^{34} value of -1.94‰.

APPENDIX E

Abbreviations Used

The following abbreviations of mineral names are used in this thesis:

ang - anglesite

aspy - arsenopyrite

bn - bornite

cc - chalcocite

cpy - chalcopyrite

cv - covellite

gn - galena

mag - magnetite

py - pyrite

po - pyrrhotite

sph - sphalerite

ttd - tetrahedrite

800 E

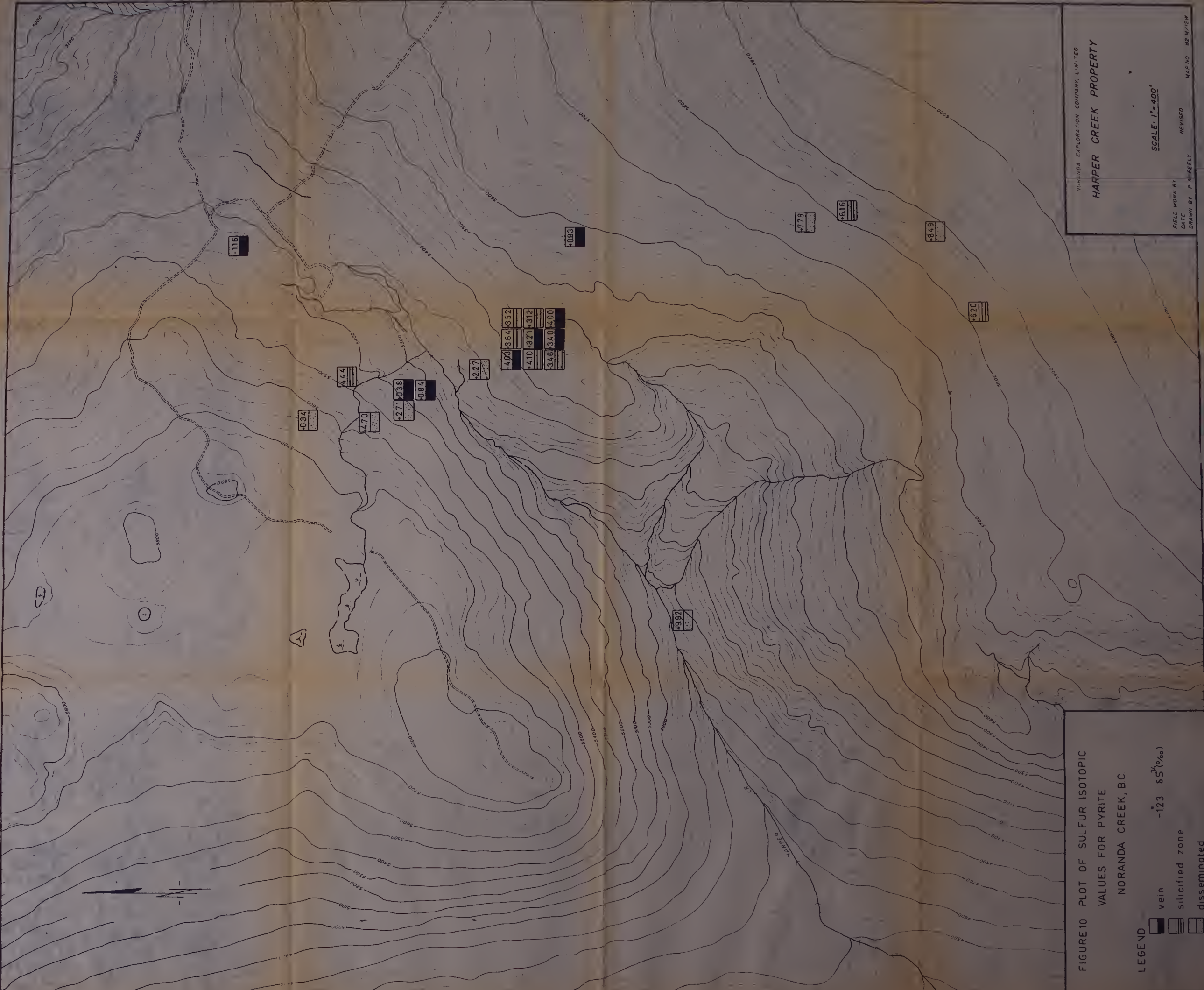


FIGURE 10 PLOT OF SULFUR ISOTOPIC
VALUES FOR PYRITE
NORANDA CREEK, BC.

LEGEND




	vein
	silicified zone
	disseminated

-123 $\delta S^{34}(\text{‰})$

NORANDA EXPLORATION COMPANY, LIMITED
HARPER CREEK PROPERTY
SCALE: 1" = 400'
FIELD WORK BY
DATE
DRAWN BY P. N. FEELY
REVISED
MAP NO. 82 M/12W

FIGURE 11 PLOT OF SULFUR ISOTOPIC
VALUES FOR CHALCOPYRITE
NORANDA CREEK, B.C.

LEGEND

	vein	+123 δS^{34} (‰)
	ill-cited zone	
	disseminated	

LIBRARY OF THE
HARPER CREEK PROPERTY

SCALE: 1" = 400'

FIELD WORK BY
DATE
DRAWN BY J. McFEELY

B29994